Fabrication of high mobility *in situ* back-gated (311)A hole gas heterojunctions

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Using an n-type (311)A GaAs substrate we have fabricated *in situ* back-gated GaAs/(Al,Ga)As hole gases with mobilities of $\mu = 1.1\times10^6$ cm^2 V^{-1} s^{-1} at 30 mK. We have investigated both experimentally and theoretically the scattering mechanisms that limit the mobility in both the $[\bar{2}33]$ and $[01\bar{1}]$ directions. Using a combination of front and back gates to keep the carrier density constant, we can distinguish between scattering mechanisms which are primarily dependent on the carrier density and those that are sensitive to the shape of the hole wave function. This approach also eliminates complications arising from the variations of the Fermi surface anisotropy with carrier density. Our data confirms that anisotropic interface roughness scattering, arising from the nature of the (311)A GaAs surface, is the dominant scattering mechanism at carrier densities down to $p_s = 5.0\times10^{10}$ cm^{-2}. © *1997 American Institute of Physics.* [S0003-6951(97)03820-5]

In recent years high mobility GaAs/AlGaAs hole gas heterojunctions for transport studies have been fabricated on the (311)A surface of GaAs, where silicon acts an acceptor.[1–3] One of the properties of using this surface is that the mobility is found to be strongly anisotropic, the mobility in the $[\bar{2}33]$ direction being greater than that in the $[01\bar{1}]$ direction.[2,3] This anisotropy was originally attributed to the anisotropy of the valence band which results in different effective masses in the $[\bar{2}33]$ and $[01\bar{1}]$ directions.[2] However, the mobility anisotropy is too large to be fully explained by anisotropy in the Fermi surface; furthermore a large mobility anisotropy is also found in electron gases grown on (311)B GaAs substrates, where the Fermi surface is known to be circular and isotropic.[4] The mobility anisotropy in {311} systems in now believed to be related to the surface structure of {311} GaAs. Both electron diffraction[5] and scanning tunneling microscopy (STM) studies[6] of the (311)A surface of GaAs indicate that the surface reconstructs to form quasi-periodic corrugations perpendicular to the $[\bar{2}33]$ direction, with a 32 Å period and height of 2 ML (3.4±0.4 Å). It is this mesoscopic roughening of the surface that accounts for the mobility anisotropy observed in both electron and hole gases formed on {311} surfaces.[3,4]

In this letter we present transport properties of a high mobility two dimensional hole gas (2DHG) measured at 30 mK, using both a ''back'' gate situated below the 2DHG, as well as having a surface Schottky ''front'' gate. The advantages of having both gates is the ability to have independent control over both the carrier density and the shape of the hole wave function. In particular, it is possible to maintain a constant carrier density whilst moving the holes either towards or away from the heterointerface. This allows us to distinguish between scattering mechanisms which are primarily dependent on the carrier density and those that are also sensitive to the shape of the hole wave function. Furthermore, it eliminates any complications that may arise from variations of the Fermi surface anisotropy with carrier density.

The samples were grown by molecular beam epitaxy (MBE) and consisted of 200 Å GaAs, a 2000 Å $Al_{0.33}Ga_{0.67}As$ back barrier layer, 2 μm GaAs, 500 Å undoped $Al_{0.33}Ga_{0.67}As$ spacer layer, 2000 Å $Al_{0.33}Ga_{0.67}As$ doped at 1.0×10^{17} cm^{-3} and a 170 Å GaAs capping layer. The back-gate is situated only 2μm from the 2DHG such that only small biases are required and there are no inhomogeneities in the hole gas, even at low densities. The wafer was processed into an orthogonal Hall bar geometry with AuBe ohmic contacts to the 2DHG, AuGeNi Ohmic contacts to the back gate and a NiCr/Au front Schottky gate. Magnetotransport measurements were carried out at 30 mK. The back gate could be operated in the range -0.5 V$<V_{bg}<$1.1 V, and the front gate in the range -0.4 V$<V_{fg}<$0.1 V, with gate leakage currents below 2nA. The carrier density p_s was found to vary linearly both with front- and back-gate bias, such that $\partial p_s/\partial V_g$ agreed to within 8% of the values expected from the growth specifications.

Figure 1 shows the mobilities in both the $[\bar{2}33]$ and $[01\bar{1}]$ directions as a function of p_s, obtained by sweeping V_{fg} at different values of V_{bg}. At low densities ($p_s<4.0\times10^{10}$ cm^{-2}) there is little or no anisotropy. As V_{fg} is made more negative (increasing the carrier density) $\mu_{[\bar{2}33]}$ increases monotonically. In contrast, $\mu_{[01\bar{1}]}$ initially increases and then above a certain carrier density is observed to decrease. This decrease has been attributed to the increasing importance of anisotropic interface roughness scattering in the $[01\bar{1}]$ direction at high carrier densities.[3] At a fixed p_s, the mobility in both directions is observed to decrease as V_{bg} increases. In this situation, as V_{bg} is increased, V_{fg} has to decrease to maintain a constant p_s. The net effect is to push the hole wave function further up against the heterointerface thereby increasing the interface roughness scattering.

In order to understand the physical mechanisms determining the mobility in this sample, a simple calculation of the mobility in the two orthogonal directions, taking into

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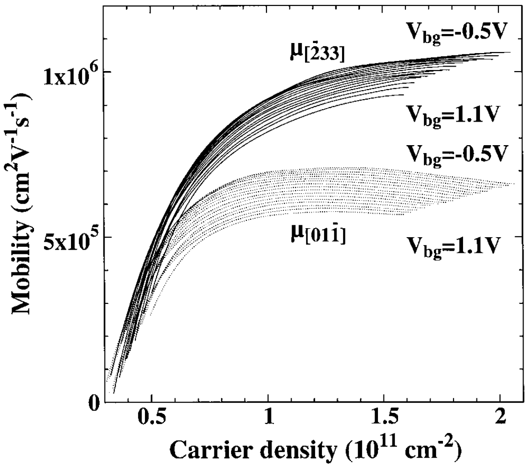

FIG. 1. Experimental mobilities as a function of carrier density for both the $[01\overline{1}]$ and $[\overline{2}33]$ directions obtained by sweeping the front-gate at incremental values of 0.05 V in the back-gate voltage.

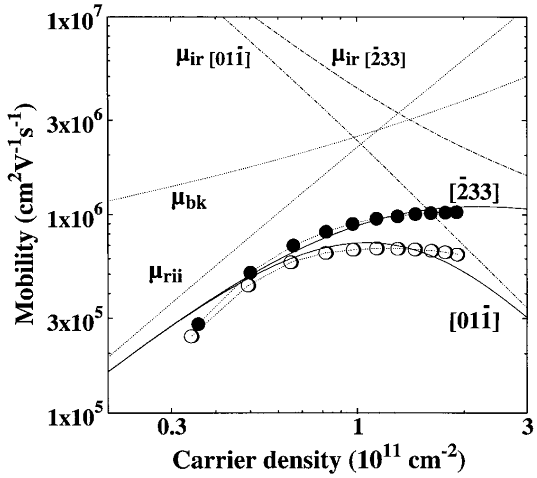

FIG. 2. Experimentally measured and theoretically calculated mobilities as a function of carrier density for $V_{bg}=0V$. The solid lines show the theoretical mobilities due to the combined scattering mechanisms in the two directions; the experimental data is marked with symbols.

account the deformation of the wave function by the front and back gate, was performed. Scattering from the following sources was considered: (i) remote ionised impurities (μ_{rii}), (ii) anisotropic interface roughness ($\mu_{ir[\overline{2}33]}$, $\mu_{ir[01\overline{1}]}$), and (iii) residual impurity scattering (μ_{bk}). The calculations were performed for T=0 K, using a Fang-Howard wave function, with screening included in the long wavelength limit. In a normal heterostructure the shape of this wave function is determined solely by p_s, which is controlled by the front gate. In our system the variational parameter b that determines the shape of the wave function $\psi(z)=b^{3/2}/(2\sqrt{2})z\exp(-bz/2)$ now depends on both p_s and V_{bg}: $b^3=8m_z^*/\hbar^2[33e^2p_s/64\varepsilon_L-3eE_{bg}/4]$. Here E_{bg} is the electric field due to the back-gate bias, m_z^* is the effective mass perpendicular to the heterojunction, ε_L is the dielectric constant of GaAs, and b^{-1} is a measure of the width of the 2D hole gas.[7,8]

The mobilities μ_{rii} and μ_{bk} were calculated as described in Ref. 9, whilst calculation of the interface roughness scattering[10] was modified such that the effective field pushing the holes up against the heterointerface F_{eff} now includes a term due to the back gate:

$$F_{eff}=\int dz|\psi(z)|^2\frac{\partial U}{\partial z}=\frac{p_s e^2}{2\varepsilon_L}+eE_{bg} \qquad (1)$$

where $U(z)$ is the potential energy. In this equation the front-gate bias is represented by the dependence of F_{eff} on p_s, and so does not appear explicitly, whereas the back gate affects both p_s and E_{bg}. In our analysis the interface roughness is characterized by three parameters: the amplitude of the roughness Δ, and two (Gaussian) correlation lengths $\Lambda_{[\overline{2}33]}$ and $\Lambda_{[01\overline{1}]}$. The anisotropy of the scattering rate was incorporated using a method described in Ref. 11.

In this sample only the heavy hole band is occupied, but the asymmetric confining potential in a single heterojunction leads to a lifting of the spin degeneracy away from $\mathbf{k}=0$ at $B=0$.[12] To account for this we have used a two band model, with effective masses of 0.23 m_e and 0.38 m_e for the two hole species,[3] but have neglected the possibility of intersubband scattering. Finally, the mobilities due to the various scattering mechanisms were combined using Matthiessen's rule, to obtain the total mobilities $\mu_{[\overline{2}33]}$ and $\mu_{[01\overline{1}]}$.

Figure 2 shows both the experimental and theoretical values of $\mu_{[\overline{2}33]}$ and $\mu_{[01\overline{1}]}$ as a function of p_s, for $V_{bg}=0$ V. The dashed lines show the calculated mobilities for the various scattering mechanisms, using the following parameters: $N_{doping}=0.6\times10^{17}$ cm^{-3}, $N_{bk}=5\times10^{13}$ cm^{-3}, $\Delta=2$ Å, $\Lambda_{[\overline{2}33]}=130$ Å and $\Lambda_{[01\overline{1}]}=32$ Å. These parameters agree well with the experimental growth conditions used, and with the size and height of the mesoscopic surface roughness observed in Ref. 6. The same parameters were found to give good agreement between theory and experiment for all back-gate biases studied. From the calculations we see that at high p_s the mobility is limited by interface roughness scattering and is thus highly anisotropic. As the carrier density is reduced the dominant scattering mechanism changes from interface roughness to remote ionised impurity scattering, and the mobility thus decreases and becomes more isotropic. The experimental data is in good agreement with the calculated mobilities, although we find that at low p_s the mobility anisotropy does not disappear as fast as the calculations suggest. Better agreement with the experimental data at lower carrier densities can be achieved by altering the correlation lengths $\Lambda_{[\overline{2}33]}$ and $\Lambda_{[01\overline{1}]}$. By using larger island sizes in the calculations, it was possible to reproduce the mobility anisotropy observed at low carrier densities, but significantly worse agreement was then found at higher carrier densities. These results are consistent with the STM studies of the (311)A surface: at high carrier densities the mobility is dominated by scattering from the quasi-periodic (32 Å) corrugations and is thus highly anisotropic. At lower carrier densities it is the large elliptical islands that are important in determining the interface roughness scattering.

We now turn to the effects of keeping the total carrier density constant, whilst using both gates to move the holes towards or away from the heterointerface. Figure 3 shows the mobility ratio $\mu_{[\overline{2}33]}/\mu_{[01\overline{1}]}$, measured at several different carrier densities as a function of V_{bg}. For all densities mea-

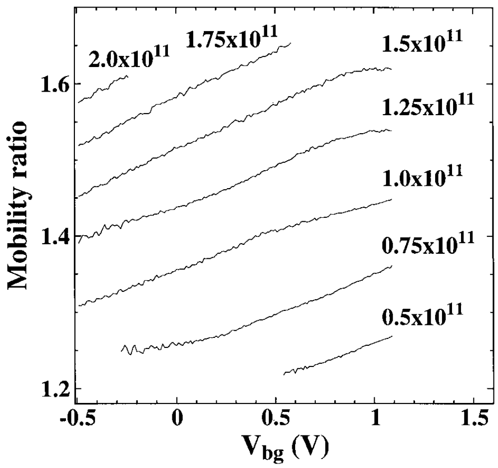

FIG. 3. The measured mobility ratio, $\mu_{[\bar{2}33]}/\mu_{[01\bar{1}]}$ as a function of V_{bg} for different carrier densities (cm^{-2}).

sured, the effect of increasing V_{bg} (whilst decreasing V_{fg}) is to increase the mobility ratio. By increasing V_{bg} we are effectively pushing the holes up against the heterointerface leading to a reduction in the mobility in both the $[\bar{2}33]$ and $[01\bar{1}]$ directions. Since interface roughness scattering is more important in determining the mobility in the $[01\bar{1}]$ direction than the $[\bar{2}33]$ direction, $\mu_{[01\bar{1}]}$ will decrease more rapidly with V_{bg} than $\mu_{[\bar{2}33]}$, hence the increase in the mobility ratio. Figure 4 shows a theoretical fit to the experimental mobilities in the $\mu_{[\bar{2}33]}$ and $\mu_{[01\bar{1}]}$ directions as a function of V_{bg}. The same fitting parameters are used as in fig. 2. It can be seen that both the background and remote ionised impurity scattering rates are almost independent of the backgate bias, as they are primarily determined by the the Fermi wave vector k_F (and hence by p_s). The interface roughness scattering, however, is sensitive to the shape of the wave function, so increasing V_{bg} causes the mobilities in both the $[\bar{2}33]$ and $[01\bar{1}]$ directions to decrease, although not at the same rate. The fit is shown here for one carrier density, but was found to be in good agreement for all carrier densities presented in fig. 3. The inset to fig. 4 shows a good fit to the mobility ratio obtained from modeling the data at one fixed carrier density confirming the validity of the simple model.

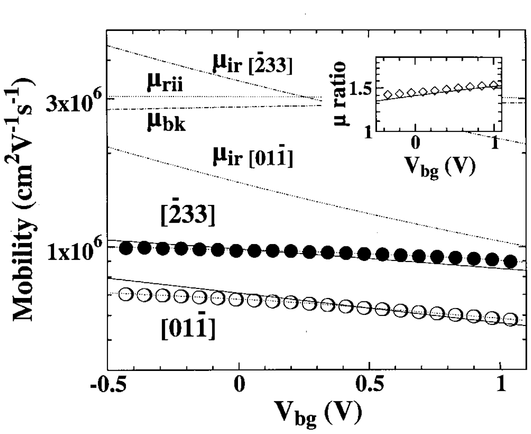

FIG. 4. Experimentally measured and theoretically calculated mobilities as a function of V_{bg} for $p_s = 1.25\times10^{11} cm^{-2}$. The inset shows the measured (symbols) and calculated (solid line) mobility ratio.

In summary, we have reported the fabrication of the first *in situ* high mobility back-gated GaAs-AlGaAs 2D hole gas. The scattering mechanisms limiting the mobility have been investigated both theoretically and experimentally and related to recent STM studies of the (311)A GaAs surface. In particular, we have demonstrated how a combination of back and front gates can be used to deform the hole gas wave function and therefore alter the relative importance of interface roughness and ionised impurity scattering at constant carrier density. In future, such devices as these will be important for studies of bilayer hole systems and zero-field spin splitting in single hole gases.

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